Accuracy and Consistency of Broadcast GPS Ephemeris Data

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BIOGRAPHIES

David Jefferson has been at NASA/Caltech's Jet Propulsion Laboratory for nine years. In that time, has primarily served as lead analyst for JPL's precise GPS orbit contribution to the International GPS Service (IGS). Supporting global and regional Earth science activities alike, he also assists with SCIGN (the Southern California Integrated GPS Network), a research project devoted to studying positions and velocities of ground locations thoroughout the Los Angeles basin and surrounding areas. He has a Bachelor of Science degree in Aeronautics/Astronautics from the Massachusetts Institute of Technology (1991).

Yoaz Bar-Sever is a Technical Group Supervisor at the Jet Propulsion Laboratory, California Institute of Technology. He holds a Ph.D. in Applied Mathematics from the Technion - Israel Institute of Technology (1987), and a Masters in Electrical Engineering from the University of Southern California (1993). From 1987 to 1989 he was a post-doctoral fellow at the Department of Applied Mathematics at Caltech. He joined JPL in 1989 where he has been involved in GPS technology development and its geophysical applications. His main contributions have been in the areas of GPS orbital dynamics, GPS signal modeling and in GPS meteorology.

ABSTRACT

A detailed statistical analysis of the performance of the GPS broadcast ephemerides is presented, spanning 1992 to date. Broadcast ephemrides are extracted from a subset of International GPS Service (IGS) ground stations, and their quality is assessed by comparing them to the precise GPS orbit solutions produced by the JPL IGS Analysis Center (also known as FLINN orbits). The latter are arguably at least an order of magnitude more accurate than the broadcast ephemerides and, hence, can serve as a truth model.

Typical 3-D, 24-hour agreement between recent broadcast and FLINN orbits is at the several-meter level. However, we have discovered some inconsistencies amongst the broadcast messages reported by different ground receivers which result in orbit differences as large as 300 meters. We examine these inconsistencies search for their cause. It is hoped that this study will give some insight into the level of confidence a user can place in the broadcast GPS navigation data, which can be important in real-time, near-real-time, and post-processing applications.

INTRODUCTION

Global Positioning System (GPS) position data and clock corrections are uploaded to satellites in the GPS constellation by the GPS control segment. Each satellite then broadcasts its own ephemeris data as a component of its navigation message. It is expected that all ground receivers will receive the same navigation data for each satellite they track in common. However in practice, this is not always true; user-formatted ephemeris data do sometimes vary from station to station for common satellite-epochs. We speculate that this can be due to receiver malfunction, or errors during the raw data conversion process.

METHOD

We analyzed broadcast ephemeris data from a 21-site subset of the global International GPS Service (IGS) ground network, sampled every 5 days for the approximate two-year period spanning January 1, 1998 through February 29, 2000. Specifically, the sites used for the analyses are all located in the United States, and are shown geographically in Figure 1, and listed with respective receiver types in Table 1. We have also examined, in somewhat less detail, longer term trends in the accuracy of the broadcast ephemeris.

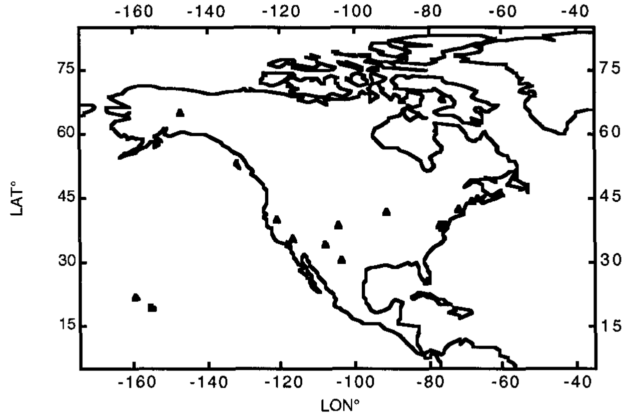

Figure 1: Map of sites from which broadcast ephemerides were analyzed during January 1, 1998 through February 29, 2000.

Table 1: Location and type of ground receivers used. Some sites changed receiver types during the span of the study.

SITE	LOCATION	RECEIVER
AMC2	Colorado Springs, CO	ROGUE SNR-12 RM, AOA SNR-12 ACT
AMCT	Colorado Springs, CO	ROGUE SNR-12
AOML	Miami, FL	ROGUE SNR-8000
BARH	Bar Harbor, ME	TRIMBLE 4000SSI
EPRT	Eastport, ME	TRIMBLE 4000SSI
FAIR	Fairbanks, AK	ROGUE SNR-8000, ROGUE SNR-12 RM
GODE	Greenbelt, MD	ROGUE SNR-8000, AOA SNR-12 ACT
GOL2	Goldstone, CA	ROGUE SNR-12 RM
HNPT	Horn Point, MD	ROGUE SNR-8000
JPLM	Pasadena, CA	ROGUE SNR-8000, ROGUE SNR-8100
KOKB	Kauai, HI	ROGUE SNR-8000, AOA SNR-8100 ACT
MDO1	Fort Davis, TX	ROGUE SNR-8000
MKEA	Mauna Kea, HI	ROGUE SNR-12 RM
NLIB	North Liberty, IA	ROGUE SNR-8000
PIE1	Pie Town, NM	ROGUE SNR-8000
QUIN	Quincy, CA	ROGUE SNR-8000
RCM6	Perrine, FL	ROGUE SNR-8000
SOL1	Solomon's Island, MD	ROGUE SNR-8000
USNA	Annapolis, MD	ROGUE SNR-8000, ROGUE SNR-12 RM
USNO	Washington, D.C.	ROGUE SNR-12 RM, AOA SNR-12 ACT
WES2	Westford, MA	ROGUE SNR-8000

Raw navigation data files are converted at several global data centers to the RINEX format. They contain broadcast ephemerides (GPS satellite positions, clock corrections, health and accuracy codes, etc.) in approximately 2-hour intervals. These data extrapolated and converted to ECEF (Earth-Centered, Earth-Fixed) X-Y-Z coordinates in 15-minute intervals. The resulting orbits are then compared with corresponding daily precise GPS orbits from the Jet Propulsion Laboratory IGS Analysis Center (JPLIGSAC), also known as FLINN orbits. Many studies, including comparisons with independent measurements have established that these orbits are consistently accurate to better than 10 cm, 3D RMS. They may serve, therefore, as truth models at the 10-cm level. Statistics and histograms are made for the differences between the two orbit sets, and outliers are studied further in accordance with the objectives stated above.

RESULTS

JPL has been providing precise GPS orbit solutions since the inception of the International GPS Service in June, 1992. Weekly reports summarizing these solutions, including broadcast ephemeris comparisons may be obtained from http://igscb.jpl.nasa.gov/mail/igsreport/igsreport.html. Below is a time-series plot of the mean weekly performance of the broadcast orbit compared with the final, precise FLINN solutions over time.

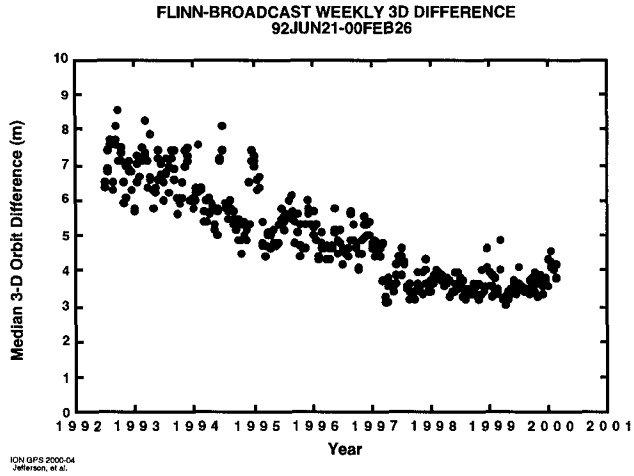

Figure 2: Time series of mean weekly 3D RMS difference between broadcast ephemerides and JPLIGSAC precise GPS orbits.

To gain insight into the quality of recent broadcast ephemerides, we focus on the two year period spanning January 1, 1998 through February 29, 2000. Initially, it was discovered that by using ALL of the data from each ground station, large outliers, on the order of hundreds of meters, were encountered (Figure 3):

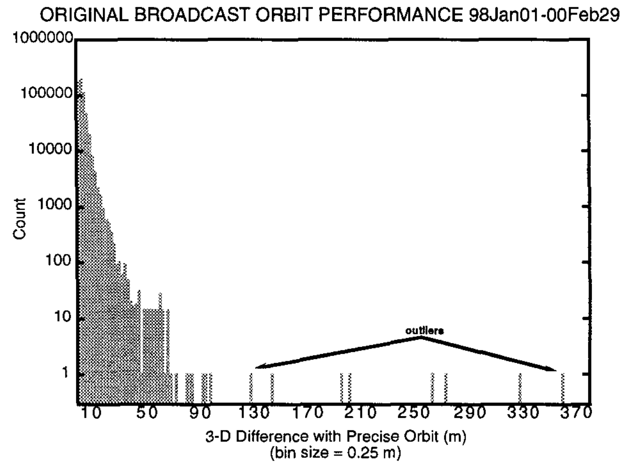

Figure 3: Two-year histogram of broadcast performance before outlier deletion.

These outliers are a consequence of variations in ephemeris data from different ground stations. For example, the largest broadcast-FLINN orbit difference of the entire study occurred for the receiver at MDO1 for PRN08 at 1998-DEC-11 13:45:00 GPS time. Further inspection of the MDO1 data revealed that the navigation message responsible this large difference was actually the record at 12:00:00, which was extrapolated to the time above. For an unknown reason, one of its ephemeris elements differ from those from other sites for this same GPS satellite and epoch. The most pronounced difference appears in the IDOT element, the rate of inclination angle of the satellite, emphasized in ***bold italics*** in Table 2 below. The value of IDOT from MDO1 at this satellite-epoch (shown as –2.8e-09 rad/s = -8 cm/s) is more than 3-sigma away from the 21-station mean for this orbital component, and resulted in the largest 3D discrepancy of the entire study, approximately 360 m. It is interesting to see the effect of this on the individual directional components of the orbit, as it is primarily manifested in the more weakly determined cross-track and along-track directions, as shown in Figure 4.

Table 2: Discrepancy in ephemeris data from different ground sites.

RINEX ephemeris data from PIE1:

```
8 98 12 11 12  0  0.0  5.626631900668e-04 4.513367457548e-11 0.000000000000e+00
    1.730000000000e+02 1.521875000000e+01 4.533403120151e-09-1.801173861504e+00
    8.046627044678e-07 9.815705241635e-03 1.068599522114e-05 5.153668783188e+03
    4.752000000000e+05-9.313225746155e-09 2.077563730549e+00 2.812594175339e-07
    9.573968447243e-01 1.701562500000e+02 1.792572823373e+00-7.933187591963e-09
   -8.143196339671e-11 1.000000000000e+00 9.870000000000e+02 0.000000000000e+00
    3.200000000000e+01 0.000000000000e+00 1.396983861923e-09 1.730000000000e+02
```

RINEX ephemeris data from MDO1:

```
8 98 12 11 12  0  0.0  5.626631900668e-04 4.513367457548e-11 0.000000000000e+00
    1.730000000000e+02 1.521875000000e+01 4.533403120151e-09-1.801173861504e+00
    8.046627044678e-07 9.815705241635e-03 1.068599522114e-05 5.153668783188e+03
    4.752000000000e+05-9.313225746155e-09 2.077563730549e+00 2.812594175339e-07
    9.573968447243e-01 1.701562500000e+02 1.792572823373e+00-7.933187591963e-09
   -2.844761352872e-09 1.000000000000e+00 9.870000000000e+02 0.000000000000e+00
    3.200000000000e+01 0.000000000000e+00 1.396983861923e-09 1.730000000000e+02
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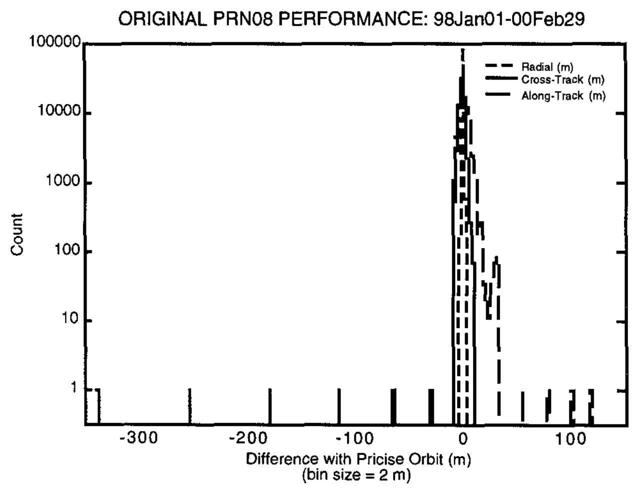


Figure 4: PRN08 comparison before outlier deletion.

This type of behvavior resulted in the need for some sort of outlier-detection scheme to remove grossly receiver-specific ephemeris points prior to comparison with the precise orbit. It was decided to use a majority-voting algorithm which involved:

- finding all ephemeris records sharing the same satellite and epoch
- computing the mean of each individual element (see Table 3)
- removing records which differed from the mean by more than 1 standard devation

Table 3: Orbital elements from a RINEX navigation data file. Although others exist, only those in the table, used in ECEF calculations, were compared.

C_{rs}	sine harmonic correction to orbit radius (m)
Δ_n	mean motion difference from computed value (rad/s)
M_0	mean anomaly at reference time (rad)
C_{uc}	sine harmonic correction to argument of latitude (rad)
e	orbit eccentricity
C_{us}	sine harmonic correction to argument of latitude (rad)
$\sqrt{A}$	square root of semi-major axis ($\sqrt{m}$)
T_{oe}	reference time of ephemeris
C_{ic}	cosine harmonic correction to angle of inclination (rad)
Ω_0	longitude of ascending node of orbit plane at reference time (rad)
C_{is}	harmonic correction to angle of inclination (rad)
I_0	inclination angle at reference time (rad)
C_{rc}	cosine harmonic corrrection to orbit radius (m)
ω	argument of perigee (rad)
ΩDOT	rate of right ascension (rad/s)
IDOT	rate of inclination angle (rad/s)

A breakdown of outliers found by this method is shown in Table 4. The percentages represent the number of duplicate data records that were removed prior to reanalysis, and are examined over different cross-sections of the data (satellites, stations, epochs, and orbital elements). Some observations:

• Most satellites had about 17-18% of their duplicate data removed. PRN11 (type Block II-R) was the most recently launched satellite during this study and had the fewest data.

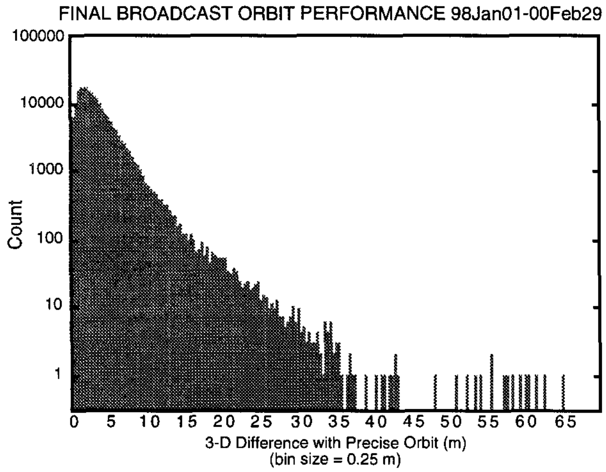
• While BARH is shown as having the fewest percentage of rejected data, the other Trimble receiver in this study had the next fewest, suggesting that Trimble receivers may be less prone to this type of error than the TurboRogue.

• Many epochs had duplicate data not exceeding the outlier criteria, hence n/a in the minimum column.

• Orbit eccentricity only marginally takes maximum status; with the exception of C_{rs}, C_{rc}, and T_{oe}, outlier data from the other elements were consistently around14%.

Table 4: Statistics for duplicate satellite-epochs removed by 1-sigma majority voting.

	Mean %	Max %	Min %
Satellites	17.3	19.4 (PRN16)	6.0 (PRN11)
Stations	87.9	99.9 (RCM5)	70.5 (BARH)
Epochs	11.5	75.4 (99mar11, 11:59:44)	n/a
Orbital Elements	11.6	14.7 (e)	0.0 (C_{rs}, C_{rc})



Once the largest outliers were removed as previously described, the magnitude of the range of differences with the precise orbit decreased from several hundreds of meters to only tens of meters. The overall performance of the "clean" broadcast orbit is shown in Figure 5; the mean and RMS of this distribution are 3.7 and 4.7 m respsectively.

Figure 5: Final two-year broadcast orbit performance.

One may alternatively want to ask what level of confidence may be placed in the broadcast orbit for different accuracy requirements. Based on the analysis presented here, a user can expect 9 m accuracy with 95% confidence, and 14 m accuracy with 99% confidence, as shown in Figure 6:

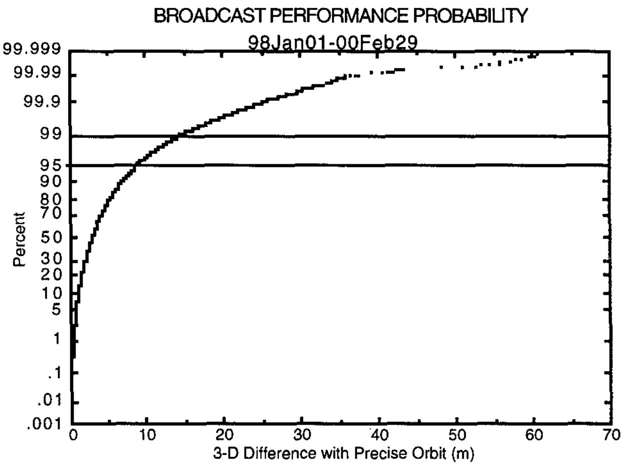


Figure 6: Overall probability of broadcast performance after removal of reference frame differences.

CONCLUSIONS

It is surmised that the broadcast GPS orbit is accurate at the 5- to 10-meter level. However, there are occasions when the receiver may make an anomalous interpretation of the broadcast signal. In post-processing applications, the effects of this can be mitigated by using various methods (majority voting, averaging, etc.) to create a merged ephemeris file that will hopefully be free of incorrect data, yielding the most accurate inputs for the end-user as possible.

ACKNOWLEDGMENTS

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